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**Laser generated electron transport experiment in a novel wire nail target**

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The transport of high intensity ($2x10^{20}$ W/cm$^2$) laser generated relativistic electrons with a solid target has been studied in a novel geometry. The targets were 20 $\mu m$ diameter solid copper wires, coated with $\sim 2\mu m$ of titanium, with an 80 $\mu m$ diameter hemispherical termination. They were illuminated by an ~500fs, ~200J pulse of 1.053μm laser light focused to a $\sim 20\mu m$ diameter spot centered on the flat face of the hemisphere. $K_\alpha$ fluorescence from the Cu and Ti regions was imaged together with extreme ultraviolet (X-UV) emission at 68 and 256eV. Results showed a quasi exponential decline in $K_\alpha$ emission along the wire over a distance of a few hundred microns from the laser focus, consistent with bulk Ohmic inhibition of the relativistic electron transport. Weaker $K_\alpha$ and X-UV emission on a longer scale length showed limb brightening suggesting a transition to enhanced transport at the surface of the wire.

The transport of laser generated relativistic electrons in solid materials is crucial to the development of fast ignition (FI) schemes [1] for inertial confinement fusion [2], particularly that variant in which the igniter laser is focused into a re-entrant gold cone [3], and also for the creation of laser generated ultra-intense x-ray sources [4,5]. X-ray fluorescence measurements have proven a useful tool for measuring the penetration of energetic electrons within a variety of solid targets [6,7]. Ohmic inhibition of electron transport occurs when the Ohmic potential from the return current stops forward propagation of the relativistic electrons [8]. Experimental data establishing the extent to which this effect limits the flow of energy into a solid target, or dense plasma, is limited. It is also an open question as to what extent high energy electrons will tend to flow along the surface of a conductor. Both of these issues are of importance in understanding the behavior of hot electrons in a re-entrant cone guided FI target.

The observation of relativistic electron transport in intermediate and high atomic number (Z) metallic targets, relevant to fast ignition and x-ray backlighting, is problematic due to the opacity of the materials to their own K-shell fluorescence. Furthermore the ability to model the transport with Particle-In-Cell (PIC) and hybrid PIC codes is determined by the size of the problem. This size is roughly proportional to the product of target mass and laser pulse length. Thin wires afford a low mass geometry for experiments that allow ready diagnostic observation and numerical modeling. In particular they allow study of Ohmic inhibition, since the hot electron driven fluorescence can be spatially resolved in the longitudinal direction. It is practically challenging to irradiate the end of a sub-50 $\mu m$ diameter wire with a high intensity short pulse laser. Employing a cone interface with the wire, such as is described in ref. 9, adds substantial additional mass and the joint between the wire and the cone, as well as the geometry of the cone itself, add unwanted complexity.

We present an experimental study using wire 'nail' targets. These are 20 $\mu m$ diameter solid Cu wires with an approximately 80 $\mu m$ diameter, roughly hemispherical termination. They are fabricated by melting the tip of the wire with a pulse of Nd:YAG laser light, and then machining down the resulting melt-globule. The heating is performed in an inert atmosphere (argon) to prevent oxidation. The machined flat surface of the 'nail head' has ~80μm diameter. The Cu nail targets employed in this experiment were also sputter coated with 2 $\mu m$ of Ti prior to the machining. An ~ $90^{O}$ bend ~ 1mm from the flat face of the nail head is formed allowing the farther end of the wire to be mounted vertically on an aluminum post (with non-electrically-conducting glue) with the ~1mm long section, terminated by the nail head, horizontal. The fabrication of the targets had some irreproducibility in radius of curvature of the nail head and the hemisphere was also sometimes offset relative to the wire axis. The nail-head is approximately an order of magnitude less massive than the cones employed in the experiment described in ref. 9, and represents only around 50% of the mass of the horizontal portion of the wire. In addition to these nail targets, 50 $\mu m$ Ti wire targets (without nail-head) were also employed, although results here were somewhat compromised by the target being of comparable diameter to the pointing accuracy of the laser. With these targets it was clear from the pattern of emission observed that in most shots the 50 $\mu m$ Ti wires were struck off center.

The targets were illuminated by an ~500fs, ~200J pulse of 1.053μm laser light from the Titan laser [10] in a ~ 20 $\mu m$ diameter spot centered with 20 $\mu m$ pointing accuracy [11] on the flat face of the nail head. A pre-plasma is formed at this location due to the amplified spontaneous emission pre-pulse which is roughly a 3ns pulse with an intensity of ~$10^{13}$W/cm$^2$.

The diagnostic layout is shown in figure 1. Two spherically bent Bragg crystal monochromatic 2-D x-ray imagers, one set up to view Ti $K_\alpha$ radiation at 4.5keV (resolution ~20µm, magnification 11x) and the other to observe Cu $K_\alpha$ emission at 8keV (resolution ~20µm, magnification 7x) were employed to record the fluorescent emission from the targets [12] . X-UV emission at 68eV (resolution ~12µm, magnification 11x) and 256eV (resolution ~10µm, magnification 11x) was also collected by multilayer mirror imagers [13]. These time integrated records show the thermal emission from the plasma in contrast to the $K_\alpha$ diagnostics, which only record emission generated by the hot electrons.

Fig. 2 illustrates typical data from a single shot. In this figure, scale bars have been corrected for the angle of view to show distances along the horizontal wire, with the exception of the 256eV image (d) in which the scale is correct for measurements in the vertical direction.

The $K_\alpha$ channels both show bright emission from the nail head and a quasi exponential fall off of brightness along the wire from the nail head with a scale length of about 150µm. Figure 3 shows a line out taken from the Cu imager. The wires are transparent to their $K_\alpha$ fluorescence (attenuation lengths are 22 and 20 µm for Cu and Ti respectively). The decay of the emission is qualitatively consistent with bulk Ohmic inhibition of the hot electron transport [14].

A 50 $\mu$m solid Ti wire with no nail head irradiated on its flat end showed limb brightened Ti $K_\alpha$ emission extending around the 90 degree bend in the wire (which was mounted in a similar fashion to the nail targets, as described earlier); see fig. 4. The scale for the main image is corrected for the view angle such that length along the horizontal wire is correct. The scale in the plot below is appropriate to measurements in the radial direction of the vertical portion of the wire. The observation of this limb brightening in the fluorescent emission, from a source that is somewhat transparent to its fluorescence at 4.5keV, implies preferential hot electron current flow along the surface of the wire. The fact that this limb brightening is not observed in the horizontal portion of the wire suggests that the trend to enhanced transport at the surface increases at greater distances from the nail head. Note that, given the limited resolution of the fluorescence imagers, it is not possible to establish whether limb brightening is present in the nail targets due to their smaller diameter.

Limb brightening is also observed in the X-UV emission from the wire in the data presented in figures 2c) and d). Here the situation is more complicated because the wires are highly opaque at X-UV wavelengths. The intensity of the emission observed at a particular location at the image plane corresponds to the temperature of the plasma ~ 1 radiation mean free path depth into the target. If the electron driven heating is non-uniform, such that the wire forms a relatively cold core, surrounded by a hot, optically thin, corona, then the radiation emanating from the limb will be more intense. This is a consequence of the greater thickness of hot plasma being subtended by rays extending from the limb region, at the target plane, toward the camera. If the heated layer were optically thick, then limb brightening would not be observed, since all rays would emanate from similarly hot plasma. In this case the brightness would be uniform except at the extremities, where less than a mean free path of plasma is presented along the ray to the camera. Figure 5, presents a graphical illustration of the anisotropic heating induced limb brightening effect alongside an enhanced view of the horizontal portion of the wire shown in figure 2c. It can be seen that limb brightening is present, suggesting the presence of an optically thin hot coronal layer, and, furthermore, this limb brightening becomes more pronounced with increasing distance from the nail head. The most likely explanation for this is that the hot coronal region near the nail-head is thicker, approaching the case where the emission comes entirely from a hot optically thick layer, which, as just described, would result in a uniform pattern of emission from the bulk of the wire.

In summary, the observation of limb brightening in the fluorescent and thermal emission from thin wire targets implies preferential hot electron current flow and heating at the surface. The presence of an Ohmic barrier to relativistic electron transport is suggested by the quasi-exponential decay, over a distance of ~150μm, of the fluorescent emission along the length of the wires. These data are being used to test hybrid PIC and PIC numerical models of the electron transport, in particular e-PLAS [15], LSP [16] and PICLS [17].

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## FIGURE CAPTIONS

Figure 1. Schematic of the experimental arrangement.

Figure 2. Results from a single shot onto a nail target, a) Cu $K_\alpha$ emission, b) Ti $K_\alpha$ emission, c) 68eV X-UV emission, d) 256eV X-UV emission. Similar data were collected for each of four targets fielded.

Figure 3. Lineout showing Cu $K_\alpha$ emission along a nail wire.

Figure 4. $K_\alpha$ emission image from a 50 $\mu$m diameter solid Ti wire shows limb-brightened emission extending around a $90^O$ bend. The plot below shows a lineout taken at the position of the yellow box in the main image.

Figure 5. Enhanced view of the horizontal portion of the wire shown in figure 2 c) shown above an illustration of the limb brightening effect.

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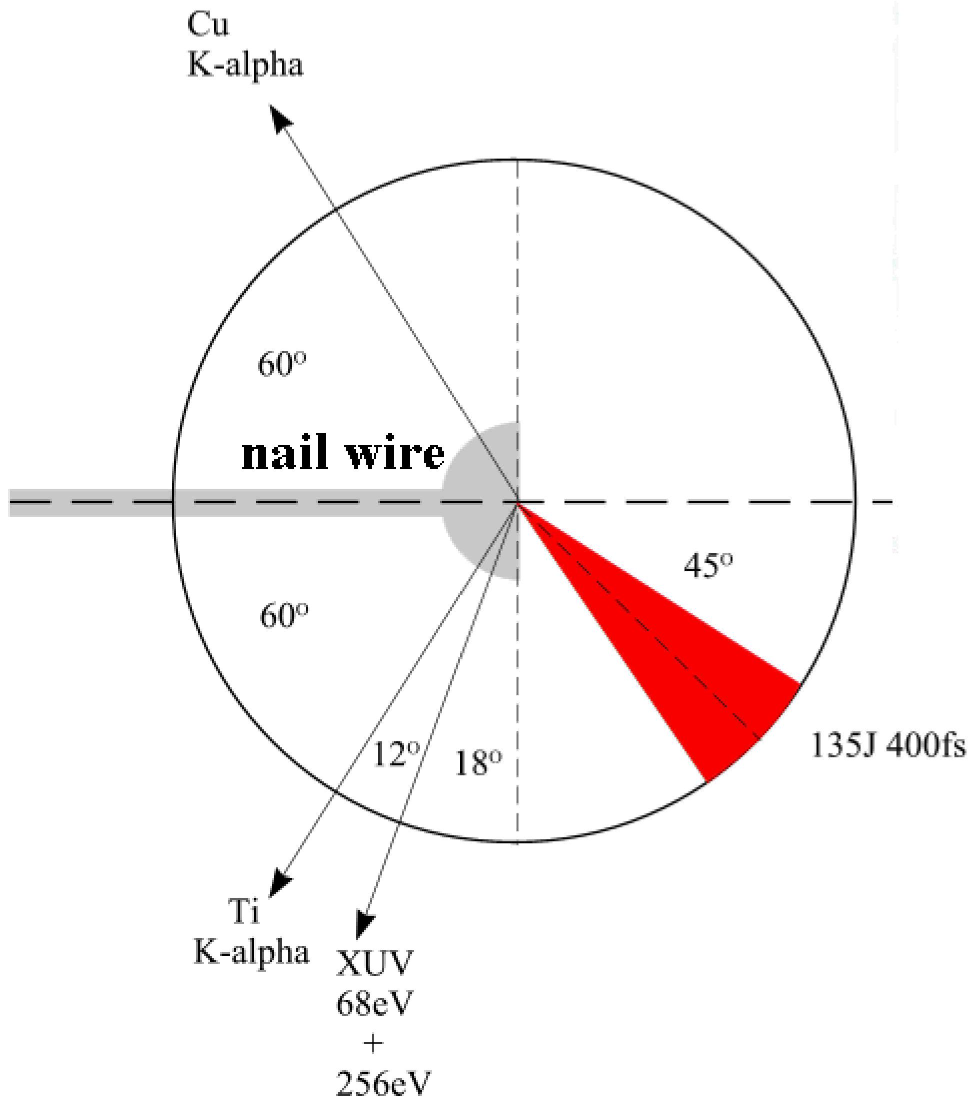

Cu
K-alpha
60°
nail wire
45°
60°
135J 400fs
12°
18°
Ti
K-alpha
XUV
68eV
+
256eV

Figure 1

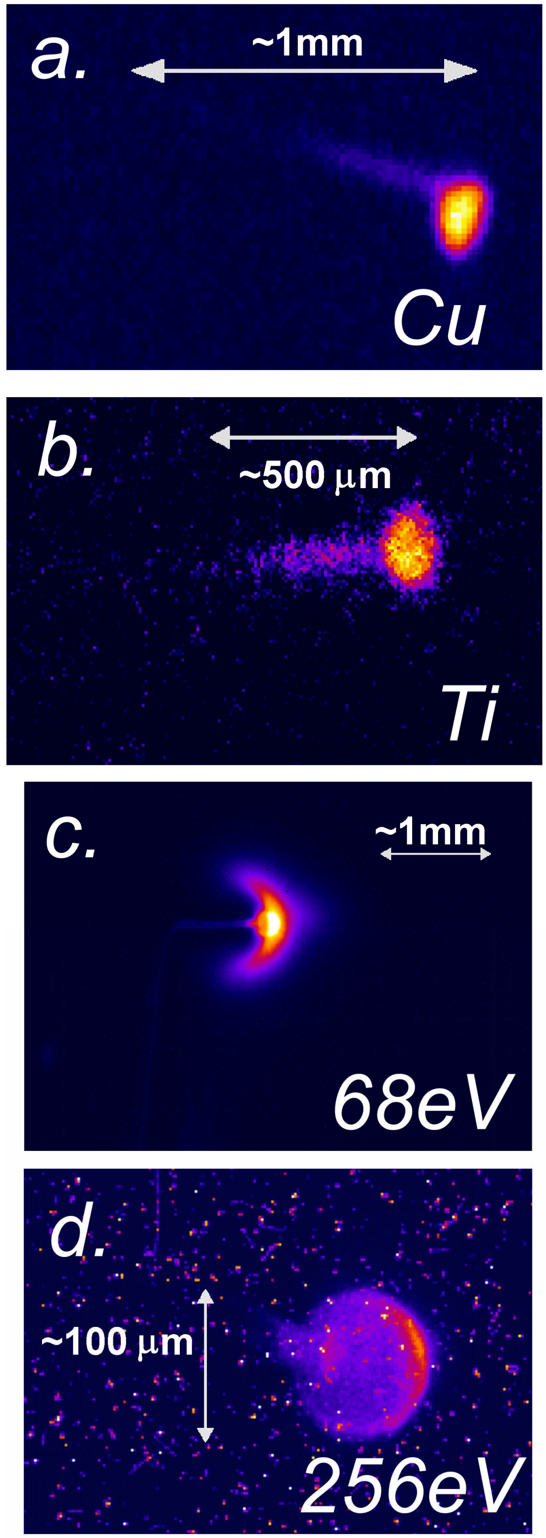
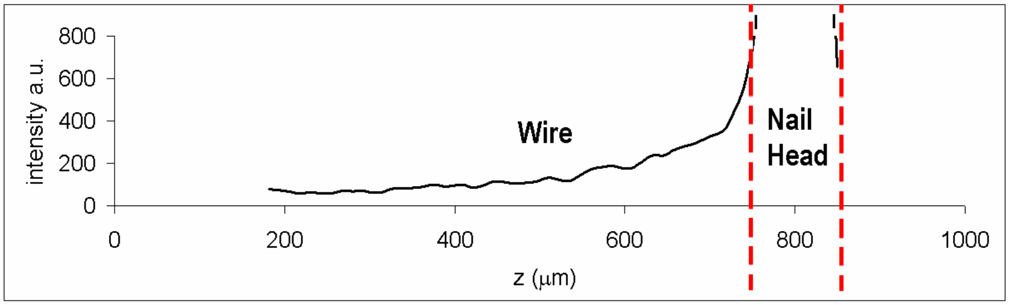
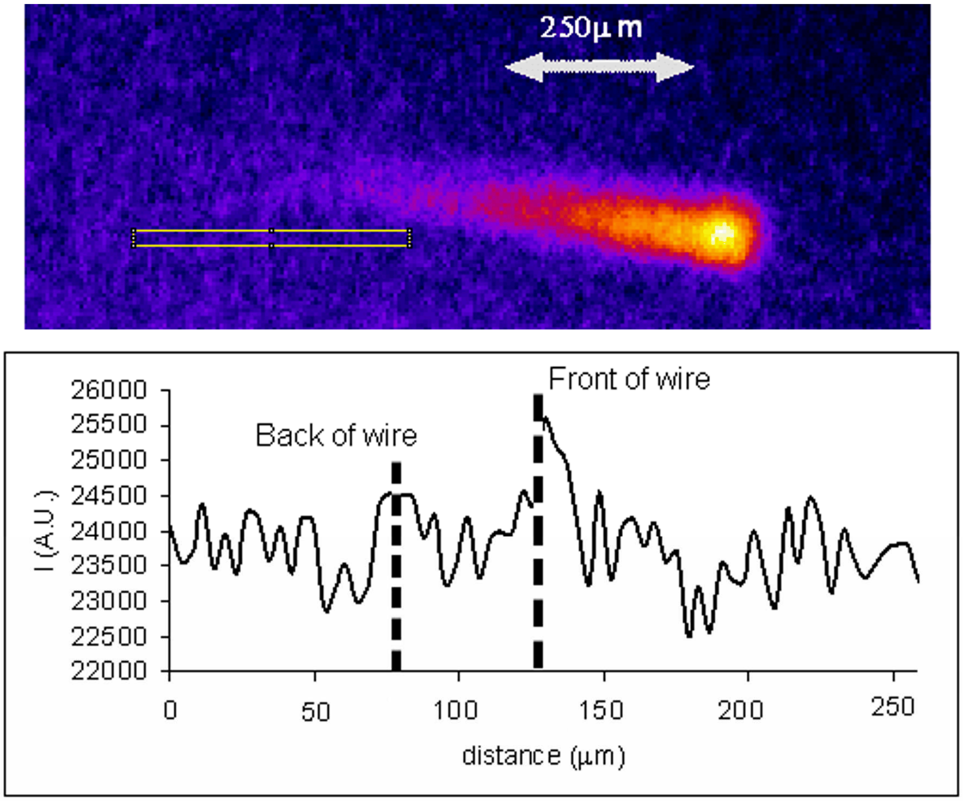



Figure 2.



intensity a.u.
800
600
400
200
0
0
200
400
600
800
1000
z (μm)
Wire
Nail
Head


Figure 3.



250µm
Front of wire
Back of wire
26000
25500
25000
24500
24000
23500
23000
22500
22000
I (A.U.)
0
50
100
150
200
250
distance (µm)


Figure 4.

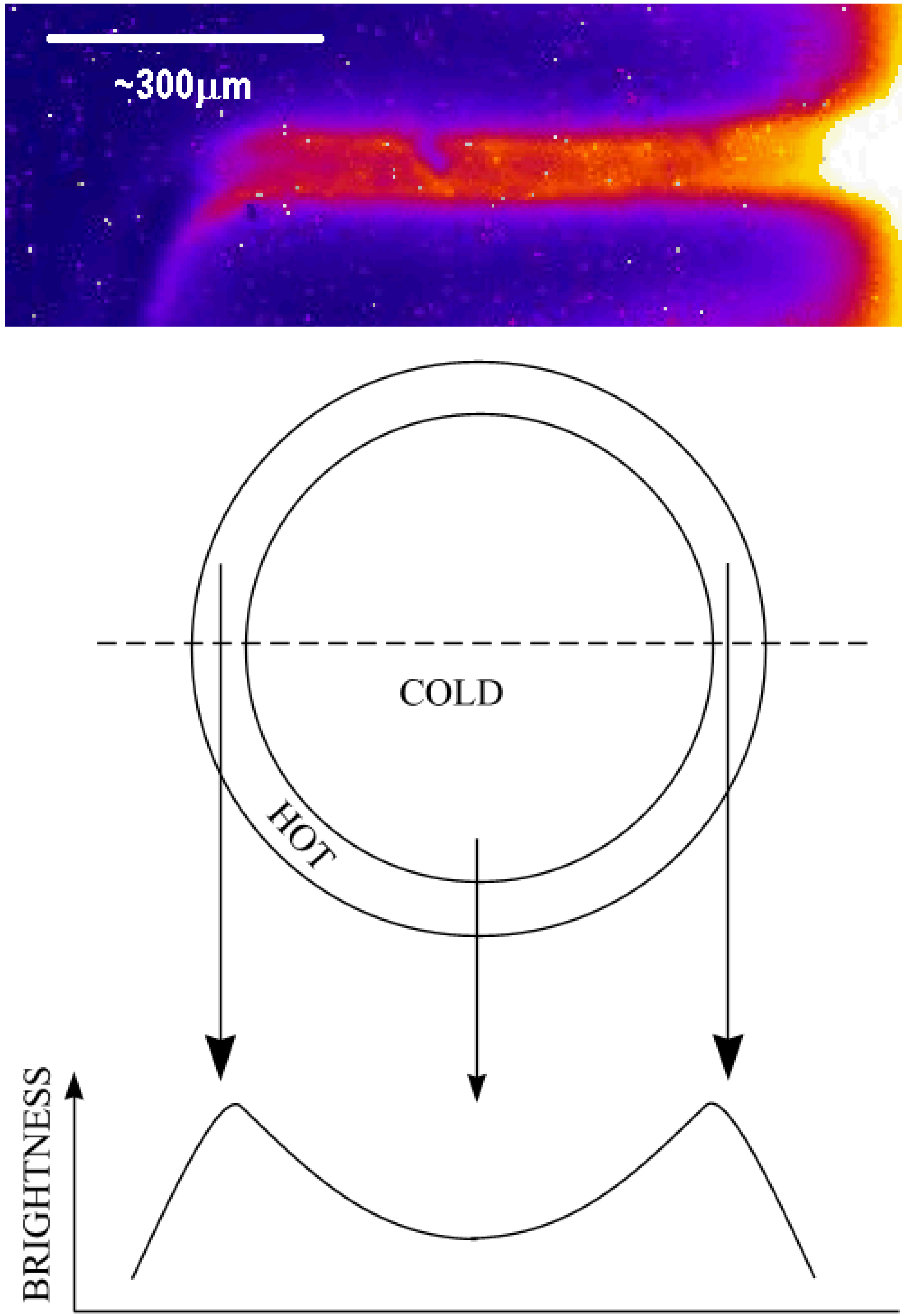



Figure 5.